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Mechanisms of single bubble cleaning

Fabian Reuter *, Robert Mettin

Christian Doppler Laboratory for Cavitation and Micro-Erosion, Drittes Physikalisches Institut, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

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ABSTRACT

The dynamics of collapsing bubbles close to a flat solid is investigated with respect to its potential for removal of surface attached particles. Individual bubbles are created by nanosecond Nd:YAG laser pulses focused into water close to glass plates contaminated with melamine resin micro-particles. The bubble dynamics is analysed by means of synchronous high-speed recordings. Due to the close solid boundary, the bubble collapses with the well-known liquid jet phenomenon. Subsequent microscopic inspection of the substrates reveals circular areas clean of particles after a single bubble generation and collapse event. The detailed bubble dynamics, as well as the cleaned area size, is characterised by the non-dimensional bubble stand-off $\gamma = d/R_{max}$, with d: laser focus distance to the solid boundary, and R_{max}: maximum bubble radius before collapse. We observe a maximum of clean area at $\gamma \approx 0.7$, a roughly linear decay of the cleaned circle radius for increasing γ, and no cleaning for $\gamma > 3.5$. As the main mechanism for particle removal, rapid flows at the boundary are identified. Three different cleaning regimes are discussed in relation to γ:

(I) For large stand-off, $1.8 < \gamma < 3.5$, bubble collapse induced vortex flows touch down onto the substrate and remove particles without significant contact of the gas phase.

(II) For small distances, $\gamma < 1.1$, the bubble is in direct contact with the solid. Fast liquid flows at the substrate are driven by the jet impact with its subsequent radial spreading, and by the liquid following the motion of the collapsing and rebounding bubble wall. Both flows remove particles. Their relative timing, which depends sensitively on the exact γ, appears to determine the extension of the area with forces large enough to cause particle detachment.

(III) At intermediate stand-off, $1.1 < \gamma < 1.8$, only the second bubble collapse touches the substrate, but acts with cleaning mechanisms similar to an effective small γ collapse: particles are removed by the jet flow and the flow induced by the bubble wall oscillation.

Furthermore, the observations reveal that the extent of direct bubble gas phase contact to the solid is partially smaller than the cleaned area, and it is concluded that three-phase contact line motion is not a major cause of particle removal.

Finally, we find a relation of cleaning area vs. stand-off γ that deviates from literature data on surface erosion. This indicates that different effects are responsible for particle removal and for substrate damage. It is suggested that a trade-off of cleaning potential and damage risk for sensible surfaces might be achieved by optimising γ.

1. Introduction

Bubbles have been employed for cleaning of solid objects since the invention of ultrasonic cleaners in the 1940s [1,2], although systematic investigations have been realised only later [3,4]. Nowadays ultrasonic cleaning is one of the major applications of acoustic cavitation, and scientific investigations of the phenomena involved are still ongoing [5–7]. It is well known that oscillation and collapse of acoustically induced gas/vapour bubbles directly at the solid surface are the cleaning agents, but the details remain partly speculative. Similar to the damage of substrate material, i.e. cavitation erosion, the immediate candidates for removal of surface contaminations are liquid jet impact and collapse shock waves. However, the existence of additional mechanisms that are too weak for damage are conceivable. For instance, in the special case of surface attached interconnected layered material (e.g. paint or ink), oscillating bubbles can penetrate gaps or cracks between substrate and contamination, and potentially loosen whole layers by leverage [3]. Cleaning of paste-like contaminations (grease)

* Corresponding author.
E-mail address: freuter@uni-goettingen.de (F. Reuter).

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has been attributed to the high shear forces during liquid jet spreading (after impact) on the surface [8], and the same mechanism appears to hold for removal of densely attached cells [9] and cell ablation [10].

In the present study, we want to focus on particulate contaminations, i.e. individual small attached solid ("dirt") particles isolated from each other, that adhere to the substrate mainly by van der Waals forces [11]. In this case the strong boundary layer flows of liquid can exert lateral forces on the particles and lead to rolling or sliding and potentially detachment. Furthermore, capillary forces from a three-phase contact line (gas/liquid/solid) are known to loosen particles [12–16]. These mechanisms come additionally to the pressure shocks from bubble collapse and jet impact at solids, but they are not expected to cause surface damage of a sufficiently flat surface.

Due to the short time scales, microscopic sizes, and partly random behaviour of ultrasonically driven bubbles in realistic cleaning systems, a closer experimental investigation of the phenomena demands for reproducible bubble events in less complex environments – for instance the nucleation, oscillation and collapse of an individual bubble. An excellent means of creation of a single bubble well controlled in space, time and size is the use of optical breakdown from a focused laser pulse in liquid [5,17,18]. This method has already been employed for general bubble dynamics studies [19] and cavitation damage tests [20]. Surface cleaning studies utilising laser generated bubbles have also been published: Song et al. [21] demonstrated the removal of particles from a silicon substrate by a quite intense laser pulse focused just below the free liquid surface near the submerged substrate. While they report on dependency of clean area on the laser power and focus distance, the number, shape, and dynamics of induced bubble(s) unfortunately remain unclear and their cleaning effects might have been based rather on a surface phase explosion [22] than on a controlled nucleation of a spherical bubble close to the substrate.

Ohl et al. [8] used a laser focusing set-up quite similar to ours and applied the technique for a paste-like contamination, apparently only for one fixed bubble distance.

Here we employ the laser technique for a systematic study of the connection of the complex bubble dynamics close to a solid surface and the particle cleaning potential. In contrast to the previous report on particle removal by laser induced bubbles [21], we analyse in detail the contributing mechanisms and the respective dependence on the bubble distance to the substrate. It should also be noted that the cleaning method investigated is distinct to the so-called laser cleaning of surfaces where the solid is directly heated by the laser irradiation in air or in a liquid film [23–25].

The bubble dynamics at a solid can be well described over a broad range of parameters by a single dimensionless number, which is the normalised stand-off distance $\gamma = d/R_{\max}$. The length d denotes the real distance between solid surface and geometrical centre of the bubble at maximum expansion (which corresponds well to the laser focus position). The expanded bubble can be considered of quite good spherical shape (although it deforms slightly because of the adjacent boundary). The radius of this sphere is called $R_{\max}$ and is used to scale d; see the leftmost sketch in Fig. 13 below for the geometry. It is well known that even rather large values of γ lead to a non-spherical collapse of the expanded bubble: An intrusion into the bubble wall is formed during collapse on the side far from the solid boundary for $\gamma <\approx 10$ [26]. When a collapsing bubble is situated closer to the solid boundary, the asphericity increases and a full liquid jet develops that traverses towards the substrate. The bubble may rebound and collapse repeatedly (typically one to three times), and its centre moves towards the boundary during this process, driven by the Kelvin impulse [27,28]. During the volume oscillations of bubble expansion and collapse a radial flow field is created at the bubble wall as the liquid follows the bubble wall movement. Additionally, shock waves are emitted, most prominently at the collapse, when the gas volume reaches maximum compression, but also when the jet hits the liquid at the opposite bubble wall or the substrate. At larger γ, a ring vortex is created that migrates towards the solid boundary [29,18]. At smaller γ, the gas phase of the bubble comes into direct contact to the solid substrate and capillary force effects from the three-phase contact line emerge.

All the mentioned phenomena are possible candidates responsible for surface cleaning. Their intensity and their location in relation to the boundary depend substantially on γ, and consequently their strength of interaction with a contamination on the substrate will do so as well. For this reason a γ-dependent investigation of the bubble dynamics in connection with cleaning is conducted which can allow for assessing the individual influence of the dynamical aspects on particle removal.

In our study, we use the laser generation technique for controlled nucleation of individual bubbles close to specially prepared glass slides with attached micro particles. Section 2 describes the experimental details and the sample preparation. To quantify the cleaning potential of the bubbles, we present in Section 3 cleaning patterns on the contaminated samples and their dependence on the non-dimensional bubble stand-off γ. As a step towards understanding the exact cleaning mechanisms of bubble dynamics, the cleaning data are compared to images taken from high speed recordings of the particle removal (Section 4). In this connection, the aforementioned possible cleaning agents will be depicted in more detail for three different regimes of γ which we identified to show distinct mechanistic features: large, small, and intermediate γ (Sections 4.1–4.3). For large stand-offs, we see a substrate cleaning only by a spreading vortex flow originating from the jetting bubble that stays far from the solid. At small γ, the bubble touches immediately the substrate, and complicated flows at the boundary emerge. The bubble dynamics at intermediate stand-offs resembles the small γ regime in the sense that the bubble touches the substrate in the rebound and/or second collapse. To analyse the more complicated situation for smaller values of γ, Section 5 discusses the gas phase contact to the substrate (Section 5.1) and the extension of the collapsed torus bubble at the solid (Section 5.2). The conclusions are drawn that the rapid liquid flows of spreading jet and close to the oscillating bubble wall are the actual cleaning agents, while capillary forces are less important. In Section 5.3, a comparison to previous results from the literature on single cavitation bubble erosion reveals significant differences between particle cleaning and material damage of flat metal substrates. In particular, an interval of γ exists where far reaching particle removal, but only low erosion potential is observed. Finally, a conclusion is given in Section 6.

2. Experimental section

The experimental set-up permits the creation of single bubbles at defined times and confined positions close to a solid boundary, the glass substrate, by focusing a laser pulse into water; see Fig. 1 for a sketch.

Individual laser pulses of 532 nm wavelength and typically 6 ns duration are created by a frequency doubled Nd:YAG laser (alternatively Brio, Quantel, France or nano S, Litron UK). To allow for a more precise focusing and thus a more spherical shape of the induced optical breakdown plasma spot, the light is expanded before focusing (VIS-YAG bm.5x, Qioptiq, Germany). Two different custom made focusing optics are employed alternatively, with numerical apertures NA = 0.12 and NA = 0.4 and working distances WD = 40 mm and WD = 12 mm, respectively. The pulse energy is